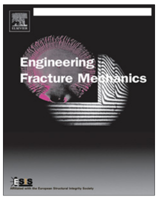
Engineering Fracture Mechanics 118 (2014) 49–65

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech



Determination of the mode I crack resistance curve of polymer composites using the size-effect law

G. Catalanotti *, A. Arteiro, M. Hayati, P.P. Camanho

DEMec, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 29 May 2013
Received in revised form 2 October 2013
Accepted 31 October 2013

Keywords:
Fibre reinforced materials
Fracture mechanics
R-curves
Size effects

ABSTRACT

This paper presents a new method to measure the crack resistance curve associated with the longitudinal failure of polymer composites reinforced by unidirectional fibres. Rather than using compact tension test specimens, the identification of the size-effect law of double edge notched specimens is used to obtain the crack resistance curve. Special emphasis is placed on the appropriate calculation of the stress intensity factor of the specimens when using quasi-isotropic or cross-ply laminates. For this purpose, both analytical closed-form solutions and numerical methods are investigated. Four different carbon-epoxy material systems, T800/M21, IM7/8552, T700/AR-2527, and T700/ACE are tested and the corresponding size effect laws and R-curves are measured. A good correlation between the crack resistance curve obtained using the size effect law and that previously measured for one of the material systems using the compact tension test is obtained. The highest value of the longitudinal fracture toughness was obtained for the T800/M21 material.

1. Introduction

The most recent analysis methods that predict fracture of polymer composite materials require not only the value of the fracture toughness, but also its relation with the increment of the crack length, i.e., the crack resistance curve. Taking the thickness of the individual ply as the representative length scale it is possible to formulate 'mesomodels' that account for both delamination (interlaminar cracking) and ply failure mechanisms (intralaminar cracking) [1–3]. The softening constitutive relation that simulates longitudinal failure, where the fracture plane is approximately perpendicular to the fibre direction, requires the fracture toughness to regularize the numerical solution [3]; however, the crack resistance curve must also be measured to identify the different regions of the softening constitutive relation so that the failure mechanisms acting at the crack tip and along the wake of the crack are properly accounted for [4].

Recently, Finite Fracture Mechanics models that use the laminate thickness as the representative length-scale have been developed to predict fracture of multidirectional composite laminates in the presence of stress concentrations [5–7]. These methods are typically used for the preliminary design and optimisation of composite structures, and are based on the simultaneous fulfilment of a stress-based criterion, which requires a stress allowable, and of an energy based criterion, which requires the fracture toughness [5–7] or the crack resistance curve [8].

---

* Corresponding author. Tel.: +351 22508 1716/1049; fax: +351 225081315.
E-mail address: giuseppe.catalanotti@fe.up.pt (G. Catalanotti).

http://dx.doi.org/10.1016/j.engfracmech.2013.10.021
0013-7944/

Nomenclature

a, a_0	crack length, initial value of the crack length
A, C	fitting parameter used in the linear regression I fit
$\acute{A}, \acute{C}$	fitting parameter used in the linear regression II fit
$\acute{E}$	equivalent modulus
f	correction factor for the dimensionality of the specimen
$\mathcal{G}_I$	energy release rate in mode I
h	thickness of the laminate
h_0, h_{90}	thickness of the 0° and 90° plies, respectively
$\mathcal{K}_I$	stress intensity factor
l	half of the length of the specimen
l_e	size of the element
l_{fpz}	length of fracture process zone
M, N	fitting parameter used in the bilogarithmic regression fit
P	applied load
P_u	peak load
$\mathcal{R}$	R-curve
$\mathcal{R}_0, \mathcal{R}_{90}$	R-curves for the 0° ply an 90° ply, respectively
$\mathcal{R}_{ss}$	steady-state value of fracture toughness
$\mathcal{R}_{0ss}$	steady-state value of the fracture toughness of the 0° ply
s_{lm}	components of the compliance matrix computed in the $x_1 - x_2$ coordinate system
t	thickness of the specimen
u_l	nodal displacement
w	half of the width of the specimen
x_1, x_2	preferred axes of the material
Y_m	nodal load
α, α_0	shape parameter, initial value of the shape parameter
β, γ	parameters used in the R-curve fit
Δa	crack increment
ϵ	error
ζ	elastic parameter
κ	correction factor
κ_0	correction factor κ for $\alpha = \alpha_0$
$\acute{\kappa}_0$	derivative, with respect to α, of the correction factor κ for $\alpha = \alpha_0$
$\boldsymbol{K}$	matrix for the polynomial fitting of κ
λ	elastic parameter
ξ	shape-parameter
ρ	elastic parameter
σ	remote stress
σ_u	ultimate nominal stress
$\hat{\sigma}_u$	corrected value of the ultimate stress
ϕ	correction factor for an infinitely long specimen
$\boldsymbol{\Phi}$	matrix for the polynomial fitting of ϕ
χ	correction factor for the orthotropy of the material
ψ	correction factor for the length of the specimen
$\boldsymbol{\Psi}$	matrix for the polynomial fitting of ψ
Avg.	average value
SD	standard deviation

Based on the above observations, it becomes apparent that reliable test methods for the measurement of the intralaminar fracture toughness[1] of composite laminates and of the corresponding crack resistance curve (R-curve) are required. While a strong emphasis has been placed on the use of compact tension test specimens [9], recent results have shown that using the current geometry of the compact tension test specimen it is not possible to measure the fracture toughness of modern resin systems that result in high values of the fracture toughness [10]. For example, in previous attempts to measure the fracture

---

[1] Two different types of failure mechanisms are usually considered in fibre reinforced composites: *interlaminar*, when crack propagation occurs between the plies of the laminate (i.e. delamination), and *intralaminar*, when crack propagation occurs within the individual plies of the laminate.